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Collective responsibility for freeway rear-ending accidents? An application of probabilistic causal models

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Abstract

Determining whether or not an event was a cause of a road accident often involves determining the truth of a counterfactual conditional, where what happened is compared to what would have happened had the supposed cause been absent. Using structural causal models, Pearl and his associates have recently developed a rigorous method for posing and answering causal questions, and this approach is especially well suited to the reconstruction and analysis of road accidents. Here, we applied these methods to three freeway rear-end collisions. Starting with video recordings of the accidents, trajectory information for a platoon of vehicles involved in and preceding the collision was extracted from the video record, and this information was used to estimate each driver's initial speed, following distance, reaction time, and braking rate. Using Brill's model of rear-end accidents, it was then possible to simulate what would have happened, other things being equal, had certain driver actions been other than they were. In each of the three accidents we found evidence that: (1) short following headways by the colliding drivers were probable causal factors for the collisions, (2) for each collision, at least one driver ahead of the colliding vehicles probably had a reaction time that was longer than his or her following headway, and (3) had that driver's reaction time been equal to his or her following headway, the rear-end collision probably would not have happened.

Keywords: Car-following; Rear-end crash; Causal inference; Markov Chain Monte Carlo

1. Introduction

Although traffic accidents on congested freeways do not typically result in fatal or even very severe injuries, they are responsible for a substantial fraction of the travel delays many of us now regard as unavoidable aspects of urban life. Reducing the frequency of these accidents could then help reduce travel delays without requiring expensive additions to highway capacity. Such accidents often occur when the vehicles in a platoon successively brake, and the braking deceleration of at least one vehicle is not sufficient to prevent it from colliding with the vehicle ahead. Preventing similar collisions would then require identifying events, which are causally necessary for accident occurrence, and then designing interventions to alter some of these necessary causes. At present, responsibility for preventing rear-ending collisions rests almost entirely with drivers, and maintaining sufficient following distance or headway is the recommended action for achieving this (e.g. Evans, 1991). When a collision occurs, responsibility is usually attributed to a lapse by the following driver who collided.

A somewhat different view of responsibility for rear-end accidents emerged from the car-following research conducted at the General Motors Research Laboratories (Herman et al., 1959; see also Gazis, 2002, pp. 21–33). Here the behavior of drivers in a platoon of vehicles was modeled using a coupled system of differential equations, where each driver's acceleration or deceleration was, after a reaction time lag, assumed to be proportional to the difference between his or her speed and the speed of the vehicle ahead. One implication of this model was that, when the product of the reaction time and the term expressing a driver's sensitivity to speed differences exceeded a threshold value, the magnitude of a change in acceleration or deceleration by the leader of a platoon was amplified by each succeeding driver, so that if the platoon was long enough a collision became inevitable. Since all drivers in the platoon were assumed to have

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the same reaction times and sensitivities, whether or not a driver collided with the vehicle ahead depended solely on his or her position in the platoon. Responsibility for the collision should then more appropriately be assigned to the platoon as a whole rather than to the colliding drivers. Using an approximate relation between acceleration noise and stability, Herman et al. also reported empirical evidence supporting the notion that individuals tend to drive near the limit where this instability occurs.

Because the General Motors car-following model did not readily allow for individual differences, it was not possible to investigate situations where some drivers may have been more responsible than others. Brill (1972) described a relatively simple kinematic model of successive braking, which supports these distinctions. Imagine a platoon of vehicles indexed in order from first to last by $k = 1, \ldots, n$, and let $v_1, v_2, \ldots, v_n$ denote the vehicle speeds. At time $t = 0$ the lead driver brakes to a stop, with deceleration a_1, and after a reaction time r_2 driver 2 also brakes to stop, with deceleration a_2, and so forth. A rear-end collision between vehicles k and $k + 1$ will be avoided as long as the distance needed by driver $k + 1$ to stop does not exceed the available stopping distance. That is,

$$x_{k+1} + \frac{v_k^2}{2a_k} \geq r_{k+1}v_{k+1} + \frac{v_{k+1}^2}{2a_{k+1}} \quad (1)$$

where x_{k+1} is the distance separating vehicle k's rear bumper from vehicle $k + 1$'s front bumper. If we let $x_{k+1} = v_{k+1}h_{k+1}$, which expresses this distance in terms of driver $k + 1$'s speed and following headway, then driver $k + 1$ will stop before colliding if his or her deceleration satisfies

$$a_{k+1} \geq \frac{v_{k+1}^2}{(v_k^2/a_k) + 2v_{k+1}(h_{k+1} - r_{k+1})} \quad (2)$$

Inequality (2) has some interesting implications. Other things being equal, the minimum deceleration required of driver $k + 1$ increases as the deceleration used by driver k increases, since $k + 1$'s available stopping distance decreases as a_k increases. Also, other things being equal, the minimum deceleration required by driver $k + 1$ increases as the difference between $k + 1$'s following headway and reaction time $(h_{k+1} - r_{k+1})$ decreases. Together these features imply, as Brill pointed out, that if each driver in the platoon is slow in reacting, so that his or her reaction time is longer than the corresponding following headway, the minimum required deceleration will tend to increase for each succeeding vehicle. If the platoon is long enough a collision again becomes inevitable and, as with the General Motors car-following model, it would appear reasonable to attribute the accident to the actions of each driver in the platoon, rather than to an egregious lapse by the last driver. But if the actions of drivers earlier in a platoon help set up the conditions for a collision, then the traditional practice of penalizing only those drivers actually involved in the collision will leave these other drivers unaware of their contributions, and so be of limited effectiveness. But how can we assess the causal contributions, if any, of these other drivers?

2. Causal concepts

An event may be present in a particular accident sequence, and there may be good reason to believe that similar events have caused similar accidents in the past, but that is not sufficient to establish that this event was a cause for the accident at hand. Baker (1990) has noted that causal attributions in road safety take a number of forms, and are often invoked to achieve rhetorical, rather than scientific, objectives. He has also given an often-used definition of causal factor as a circumstance "contributing to a result without which the result could not have occurred." Implicit in this definition is first, that removal of a causal factor should be sufficient to prevent the result, and second that one determines whether or not a circumstance is a causal factor by carrying out a counterfactual test, where what happened is compared to what would have happened had the circumstances in question been different. In practice, however, giving a rigorous yet general specification of such tests has proved somewhat daunting, the main challenge being to unambiguously specify what should count as the counterfactual condition. Since one can, with sufficient imagination, almost always describe a number of different scenarios where an accident is avoided, this test condition should involve a change that is in some sense minimal. Lewis (1973) has given a philosophical treatment of truth conditions for causal assertions, using a comparison between what actually happened and what would happen in a closest possible world where certain counterfactual assertions are true. What is meant by closest possible world was left deliberately vague, which improved the generality of Lewis's treatment but makes it difficult to apply to practical cases. Over the past 15 years or so there has been increased interest in causal inference as a component of artificial intelligence, and one especially useful approach is based on what Pearl (2000) calls a causal model. This is "a mathematical object that assigns truth values to sentences involving causal relationships, actions, and counterfactuals." (Tian and Pearl, 2000, p. 290) To construct a causal model one identifies a set of exogenous variables, a set of endogenous variables, and for each endogenous variable a structural equation describing how that variable changes in response to changes in the exogenous and/or other endogenous variables. Events are defined in terms of values taken on by the model's variables. The closest possible world where a set of variables takes on (counterfactual) values can be unambiguously defined as the outcome of a modified causal model, where the exogenous variables are set to the same values as in the actual condition, but where the structural equations associated with the counterfactual event are replaced by assignment statements. Arguably, this provides a rigorous specification of the insight underlying Baker's definition of causal factor.

To illustrate how these ideas might be applied to a freeway rear-end accident consider Fig. 1, which displays Brill's sequential braking model (in this case involving a three-vehicle platoon) as a directed acyclic graph. The nodes of the graph represent the model's variables, while the arrows indicate the presence and direction of causal dependencies. Those nodes without arrows pointing toward them (such as v_1) represent exogenous variables, while the others (such as a_{20}) represent